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Citation: Rev. Sci. Instrum. **68**, 4418 (1997); doi: 10.1063/1.1148406

View online: http://dx.doi.org/10.1063/1.1148406

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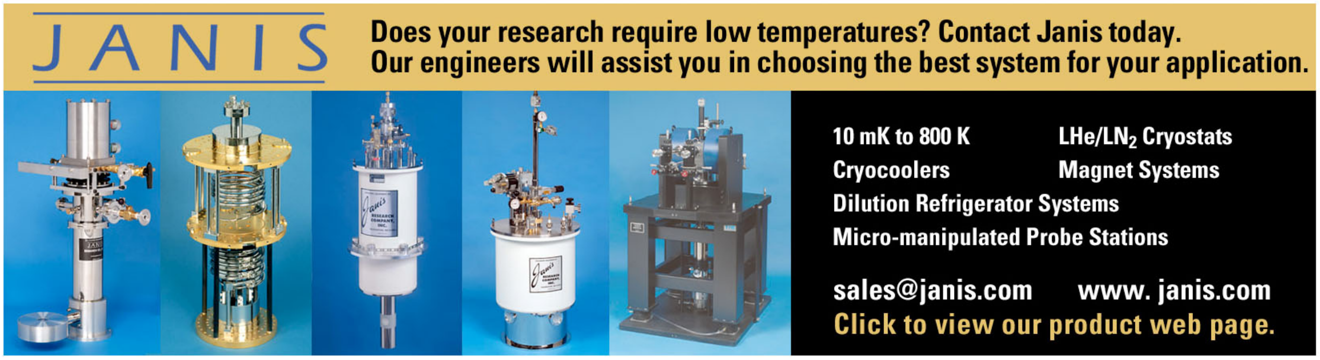

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A complex probe for measurements of turbulence in the edge of magnetically confined plasmas

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(Received 23 June 1997; accepted for publication 12 September 1997)

To improve the turbulence characterization and the estimation of the transport processes at the plasma edge, we designed and installed, in the Brazilian tokamak (TBR), a complex probe that consisted of five single Langmuir probes, a four-channel triple probe, and magnetic probes. In this work, we describe in detail this diagnostic system and present experimental examples of simultaneously measured plasma parameters and electrostatic and magnetic turbulent fluctuations in the TBR tokamak. This procedure permits to investigate any coupling between these two kinds of oscillations. Furthermore, our results confirmed that corrections due to electron temperature fluctuations are relevant for turbulence characterization. *© 1997 American Institute of Physics.* [S0034-6748(97)02312-5]

I. INTRODUCTION

Turbulent fluctuations at the plasma edge of tokamak machines are critical for the performance of nuclear fusion devices because they enhance the particle and energy transport and degrade the confinement.[1,2] Despite the large amount of experimental data obtained in the last years, the sources of these turbulent oscillations have not been completely identified yet.

To recognize these turbulence sources, it is necessary to measure the level of density and potential fluctuations and their phase difference. Nevertheless, these quantities depend on the temperature fluctuations, that is technically difficult to measure due to the high frequencies components of the temperature oscillations, similar to those observed in the density and potential fluctuations. In fact, despite the intensified studies of plasma edge turbulence in the last years, the temperature fluctuations and their correlation with other fluctuating quantities have rarely been measured.

Furthermore, in some magnetic confinement devices, as reversed field pinches, the electrostatic and magnetic fluctuations have the same driving sources.[3,4] In other devices, as tokamaks, correlation between these two kinds of oscillations is less evident, but even so they may be significant for tokamak plasma confinement.[5,6] So, to identify the turbulence process, measuring simultaneously the electrostatic and magnetic fluctuations is important.

To simultaneously measure all these parameters several kinds of complex probes have been constructed, some of them using new probe techniques.[3,7–11]

Thus, a four-channel triple-probe and a magnetic-probe array were used in the reversed field pinch REPUTE-1.[3] This system measured the mean and fluctuating plasma parameters, including three components of magnetic field, three components of electric field, electron density, and electron temperature.

Nearly identical measurements of the level of temperature fluctuations were obtained by using a swept double-probe and a triple-probe technique in the tokamak TEXT-U.[8] In another experience, a fast-swept single probe was used to measure the electron temperature and the density in a time scale that is small compared with the turbulence characteristic times.[10] A similar technique was used to measure the electron temperature fluctuations in the tokamak COMPASS.[11]

Another scheme to extend the triple-probe technique for the measurement of the electron temperature fluctuations and the fluctuation-driven transport was used in the tokamaks Phaedrus-T and TEXT-U.[12]

Despite all these previous results, none of these systems were designed to measure simultaneously all the relevant amplitudes and phase differences necessary to investigate accurately the sources of turbulence and transport in the edge plasmas.

In this work we used an especially designed system of Langmuir probes. Besides a common single probe and four single probes to measure floating potential and ion saturation current fluctuations, this probe system contains also a modified triple probe with four tips to measure the (average and fluctuating) electron temperature. These measurements allowed to determine the influence of temperature fluctuations on electrostatic fluctuations and their influence on the plasma-edge transport. Furthermore, this system contained

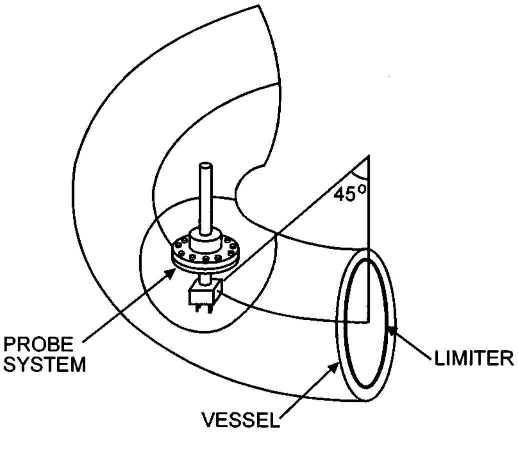

FIG. 1. View of the probe assembly mounted on the tokamak TBR.

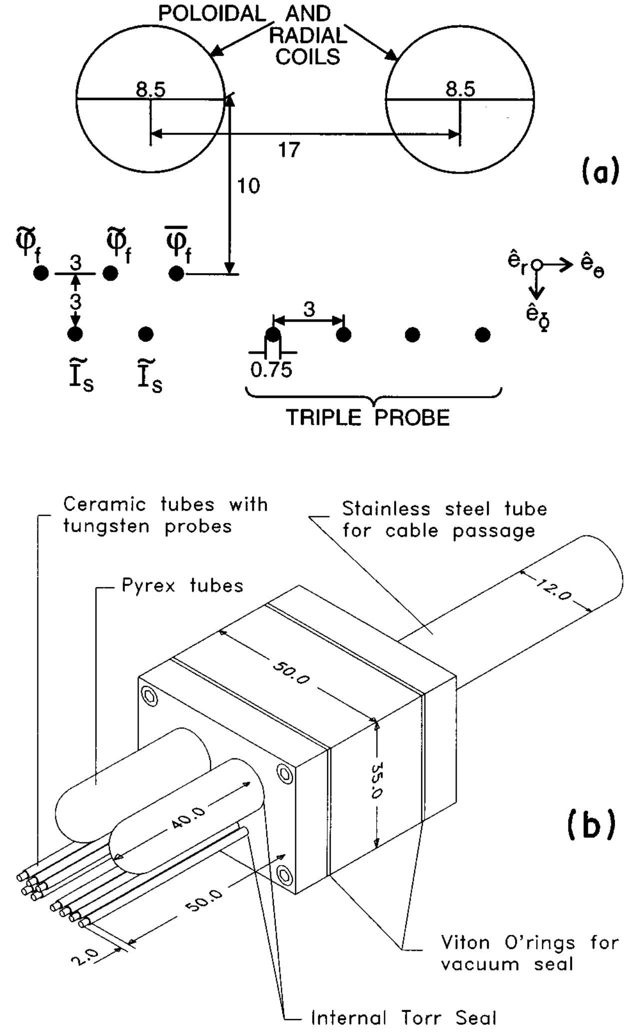

FIG. 2. (a) Scheme showing the position of the probe tips and magnetic coils; (b) technical drawing of the probe assembly (all dimensions are in mm).

also two pairs of magnetic coils to obtain the poloidal and the radial components of the magnetic field fluctuations. Measurements in the neighbor probes gave oscillations with the same amplitudes and high correlation. Thus, we also determine the correlation between electrostatic and the magnetic fluctuations.[13]

The outline of this article is as follows: Section II gives a description of the measurement system and the techniques used. In Sec. III we present some examples of measurements. Section IV contains some discussions and results.

II. MEASUREMENT SYSTEM AND TECHNIQUES

The complex probe consists of nine electrostatic probe tips, grouped along two poloidally oriented lines, and two sets of magnetic coils. The probe assembly was mounted in a port at 45° from the limiter oriented clockwise in the toroidal direction, as shown in Fig. 1.

Figures 2(a) and 2(b) show the disposition of the electrostatic probes allocated in the two lines. One line has three tips and the other six tips. The tip separation is 3 mm. There is a small poloidal displacement between the probes of the two lines to avoid any shadow effects between probes. The collecting parts of the electrostatic probes are made of a tungsten wire 0.75 mm in diameter and 2 mm long.

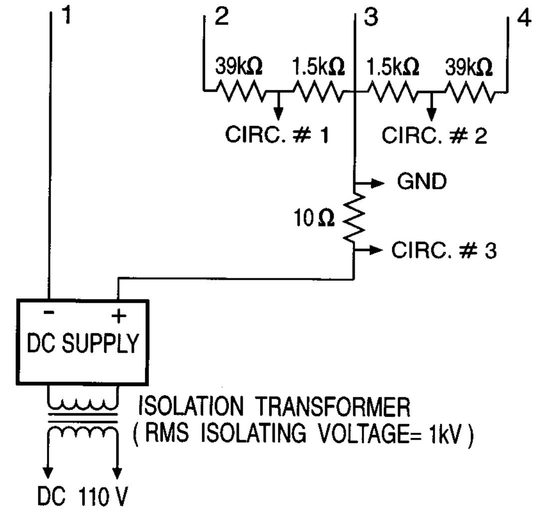

FIG. 3. Scheme of the triple-probe arrangement.

The left four tips shown in the figure, two in each line, are used to measure the floating potential and the ion saturation current fluctuations in the poloidal direction. Near these tips there is another tip used to measure the average value of the floating potential. Finally, four tips working as a triple probe are aligned with the tips used to measure the ion saturation current fluctuations.[3,8,12,14]

A triple-probe drive circuit is similar to that used in Ref. 3 and is shown in Fig. 3. The ion saturation current flows between tips 1 and 3 and passes through the 10 Ω resistor and the dc power supply. The resistor is used to detect the ion saturation current. In our work, two tips (2 and 4) are used to determine the floating potential instead of one used in the ordinary triple probes.[14] This is done to cancel the phase delay error[12] that occurs in the standard arrangement.[14]

The voltage of the dc power supply, V_{dc}, was adjusted so that the condition $V_{\mathrm{dc}} > 4T_e/e$ is satisfied. Then, if the saturation currents are well defined, the mean and fluctuating values of T_e are determined by the relation

$$T_e = e(\varphi_3 - \varphi_f)\ln 2, \tag{1}$$

where φ_3 is the voltage in the probe tip 3 and $\varphi_f = (\varphi_2 + \varphi_4)/2$.

Three circuits identical to the shown in Fig. 4 were used in the triple probe to measure mean and fluctuating voltages. Two circuits measure the voltage of the probes 2 and 4, and the third circuit measures the voltage drop in the 10 Ω resistor. These voltages permit to calculate the electron temperature and the ion saturation current (average and fluctuating values). The power supply applies a potential of ~120 V between probes 1 and 3. This circuit is used as a gain adjustable isolation amplifier and couples the probes with the digitizer (LeCroy 2264). The amplifier bandwidth is from 5 to 250 kHz, and the sampling rate is 1 MHz. So, the circuit has basically the functions: to isolate electrically the probe tips

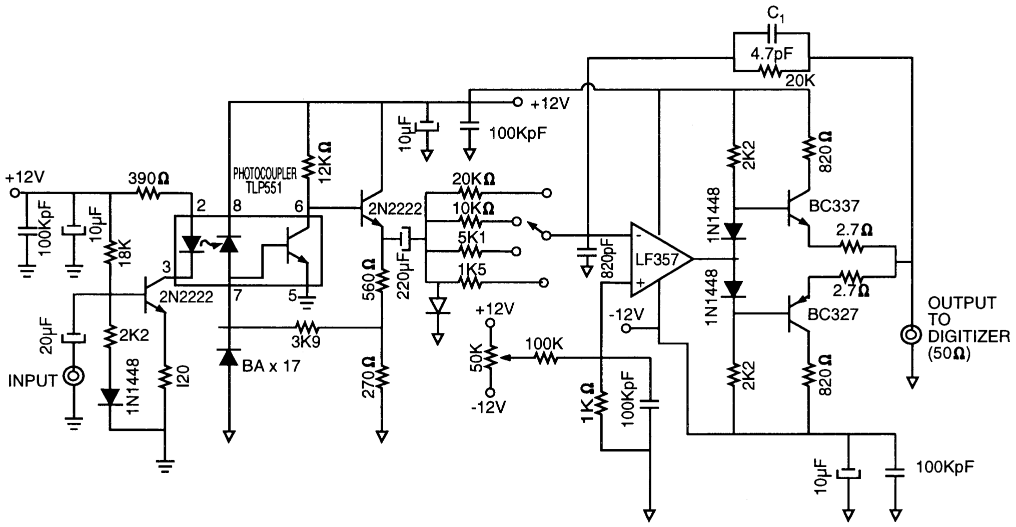

FIG. 4. Circuit for the measurement of triple-probe signals.

from the digitizer (avoiding ground loops), to permit the gain adjust of the signal, and to give the impedance matching the digitizer input (50 Ω).

The probes used to measure the ion saturation current and floating potential fluctuations are coupled to circuits that are similar to those used in the triple probe. The amplifier cut-off frequency is ~3 kHz and the higher cut-off frequency is ~250 kHz. Figures 5(a) and 5(b) show the circuits used to detect respectively the ion saturation current and the floating potential fluctuations. In the second circuit the output low impedance signal is sampled through a 10 kΩ potentiometer and applied in the shield of the input coaxial cable to reduce the cable capacitance effect. The circuit used with the probe that measures the average value of floating potential has a lower cut-off frequency.

The signals of the radial and poloidal components of the fluctuating magnetic fields are detected with magnetic probes [mounted on the complex probe system (Fig. 2)] that are inside the vacuum vessel, always in the shadow of the limiter. These probes are at the same toroidal location.

The magnetic probe configuration consists of two sets of two coils, each disposed radially, one coil is for measuring the poloidal component and the other for the radial component of the magnetic field. The diameter of each coil is 7 mm. The coils for poloidal magnetic field detection are made with 60 turns of copper wire (No. 35 AWG), while more turns are used for radial field detection due to the lower values of radial magnetic field. These coils directly measure the voltage signal that is $V=(N\times A)\ dB/dt$, where N is the number of turns of the coil and A its area. Since the shape of the coils is not exactly a circle, the $N\times A$ is experimentally determined by using the known magnitude of a sinusoidal varying magnetic field. Thus, the measured areas are about 3×10^{-3} m^2 for poloidal field detecting coils and 4×10^{-3} m^2 for radial field detecting coils. The probes were protected with cylindrical covers of pyrex glass and are at a fixed poloidal position. However, they can be moved along the minor radius direction, but not closer than 3 mm outside the limiter to avoid plasma contamination and thermal deposition.

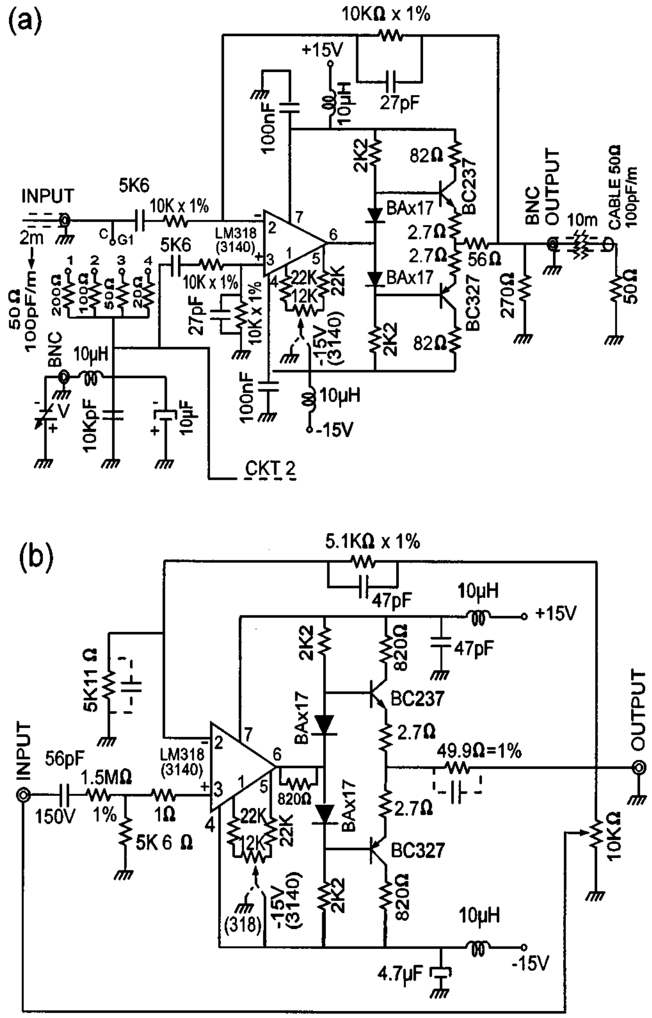

FIG. 5. (a) Circuit for the measurement of floating ion saturation current, (b) circuit for floating potential fluctuations.

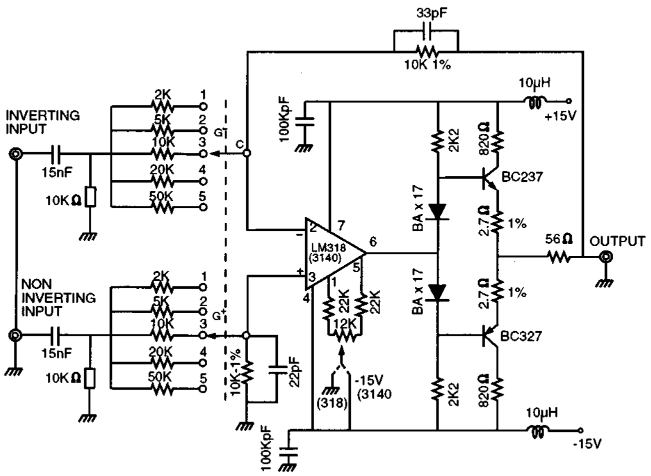

FIG. 6. Circuit for the measurement of fluctuating magnetic field components.

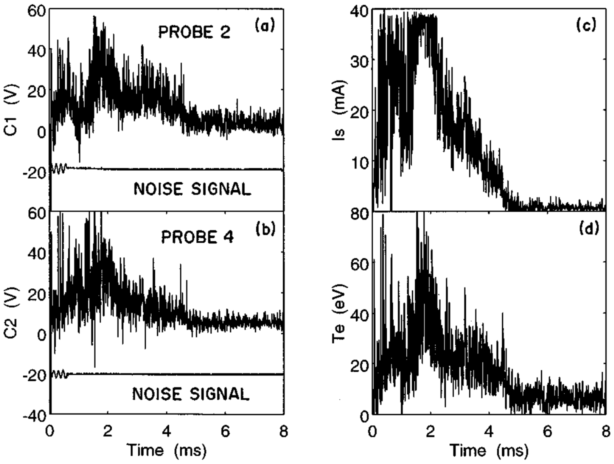

FIG. 7. Time behavior of triple-probe fluctuating potential from circuits (see Fig. 3) (a) Probe 2 and (b) Probe 4, (with the noise signal in the same scale, shifted to -20 V); (c) time behavior of the ion saturation current; (d) time profile of T_e obtained from circuits $C1$ and $C2$.

A schematic diagram of the circuit associated with these coils is shown in Fig. 6. We constructed four of these circuits with reliable measurements until ~250 kHz.

The probe assembly was mounted on a single shaft that can be moved radially between shots.

The probe was mechanically designed for high vacuum conditions. Simplicity, easy maintenance, and absence of virtual leaks were taken into account. To make the vacuum seals we used viton O rings and Torr-Seal. To avoid impurity contamination, we take special care with the problem of plasma-probe interaction.

All fluctuation signals were sampled at 1 MHz, analog

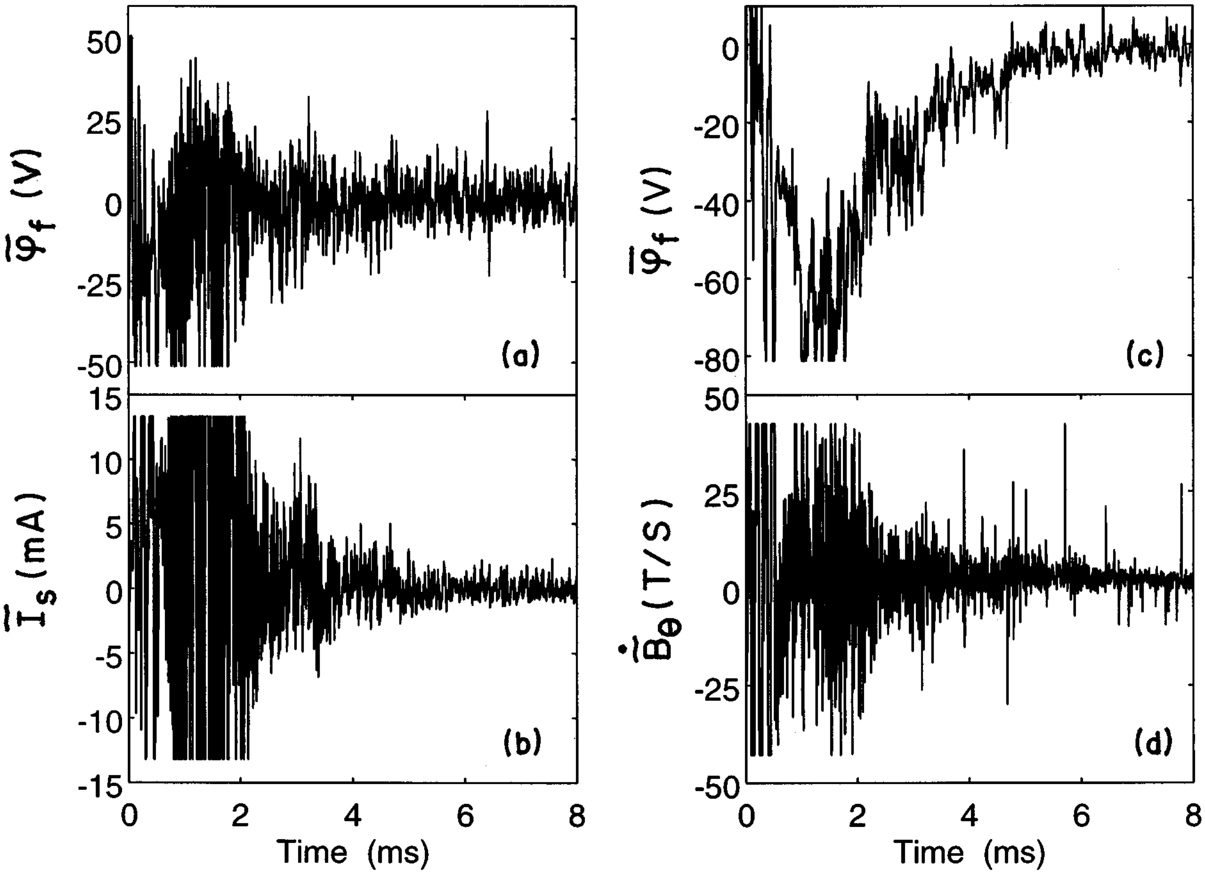

FIG. 8. Time behavior of (a) the floating potential, (b) ion saturation current, and (c) mean floating potential, measured with the singles probes shown in scheme of Fig. 2. (d) Time behavior of poloidal magnetic field fluctuations.

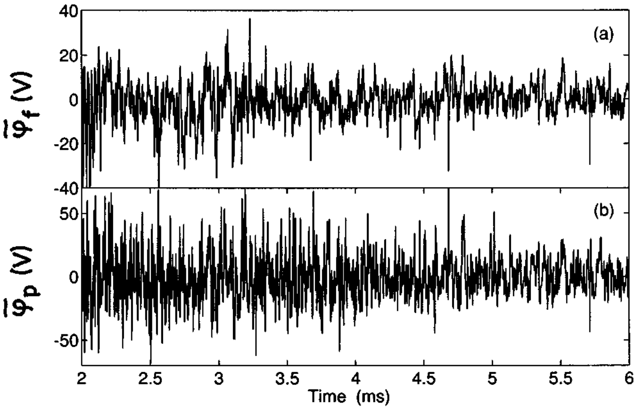

FIG. 9. Time behavior of floating potential, plasma potential with the correction of temperature fluctuations.

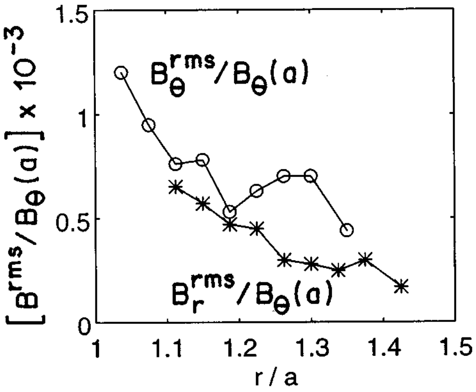

FIG. 11. Radial profile of B_0^{rms} poloidal magnetic field (○), normalized to poloidal magnetic field at the limiter. The same for radial magnetic field (*).

filtered at 500 kHz to eliminate aliasing, and recorded with an 8-bit digitizer (LeCroy 2264).

Special care was taken to reduce, to a minimum, the stray capacitance of the cables connecting the probes to the amplifier. Noise was determined for all the probes and show a very low level.

III. SOME EXAMPLES OF MEASUREMENTS

In this section we present some data obtained in the plasma edge of the TBR tokamak. This is a small tokamak dedicated to basic research, diagnostic development, and training. Its main parameters are: R (major radius) $=30\times 10^{-2}\ m$, a_v (vessel radius)$=11\times 10^{-2}\ m$, a (plasma radius)$=8\times 10^{-2}\ m$, R/a (aspect ratio)$=3.7$, B (toroidal field)$\approx 0.4\ T$, I_p (plasma current)$=6$–12 kA, T_{eo} (central electron temperature)~ 150 eV, n_{eo} (central electron density) $\sim 7\times 10^{18}\ m^{-3}$.

The probe measurements are performed during ~ 4 ms at the flat-top phase of the discharges with current of ~ 10 kA.

Figures 7(a) and 7(b) show the signals of the triple probe tips 2 and 4. The average of these two signals is the corrected floating potential. Figure 7(c) shows the ion saturation current measured with the triple probe. We used a numerical filter to separate the mean and fluctuating values of the signals. Figure 7(d) shows the typical time behavior of the electron temperature as obtained from expression (1). All these signals were taken in the boundary plasma at $r/a=0.89$. Furthermore, Figs. 7(a) and 7(b) show not only the signals, but also their noise level, which was low for all probes. To represent the noise signal in a visible form we shifted the signal of -20 V in the original scale.

The mean values of these quantities are obtained by the usual relations and the fluctuating values by the following relations[1]:

$$\tilde{\varphi}_p=\tilde{\varphi}_f+2.3\tilde{T}_e, \qquad (2)$$

$$\tilde{I}_{\mathrm{si}}/I^0_{\mathrm{si}}=(\tilde{T}_e/T^0_e)/2+\tilde{n}/n^0\{1+(\tilde{T}_e/T^0_e)/2\}-(\tilde{T}_e/T^0_e)^2/8, \qquad (3)$$

where $\tilde{\varphi}_p$ and $\tilde{\varphi}_f$ are respectively the plasma and floating potentials, $\tilde{I}_{\mathrm{si}}$ is the ion saturation current, and the superscript 0 means mean value. These expressions are written for hydrogen plasma with $T_i=2T_e$ as in TBR.[15]

These expressions permit to take into account the temperature fluctuations in the determination of plasma potential and electron density; the parameters used to calculate the edge particle and energy transport.[6]

Figures 8(a) and 8(b) show the fluctuation part of the floating potential and ion saturation current obtained by two

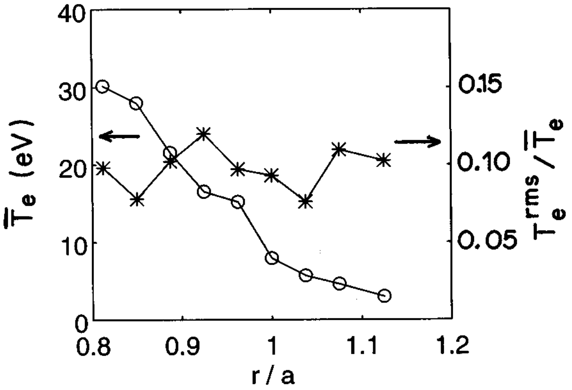

FIG. 10. Electron temperature profile (○), and the relative levels of temperature fluctuations (*).

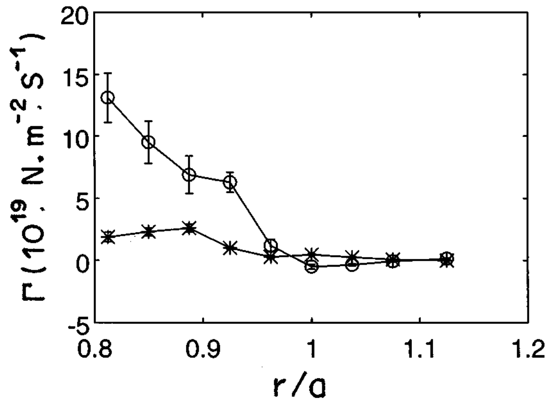

FIG. 12. Induced particle profiles with (○) or without (*) the temperature fluctuation correction.

of the four left tips of Fig. 2. The average floating potential is shown in Fig. 8(c) and Fig. 8(d) displays the time behavior of the poloidal magnetic field fluctuations.

An example of the significative influence of temperature fluctuations on the determination of the corrected floating potential, calculated by expression (2), is shown in Figs. 9(a) and 9(b). A similar effect is also obtained correcting the density fluctuations.

IV. DISCUSSION AND RESULTS

The described complex probe permitted the measurement of mean and fluctuation values of density, plasma potential, floating potential, and temperature. With the magnetic probes, we detected the radial and poloidal fluctuations of the magnetic field and these signals were used to calculate their correlation with the fluctuating parameters obtained from electrostatic probes.

In this section we present some experimental examples obtained in the TBR plasma edge using the complex probe described in this article.

Figure 10 shows the electron temperature profile and the root mean square (rms) values of the temperature fluctuations. The relative levels of temperature fluctuations, about 15%, had the same order of magnitude as those obtained for density and fluctuating potential; therefore, they must be taken into account to estimate the plasma-edge turbulence correctly.

Figure 11 shows the edge profiles of the fluctuating poloidal and radial magnetic fields, in the radial interval $1.03 < r/a < 1.35$, normalized to the equilibrium poloidal magnetic field at the limiter. From these data we obtained the correlations between electrostatic and magnetic fluctuations.[13] Moreover, we confirmed the negligible contribution of the magnetic fluctuations on the transport of particles and energy for tokamak devices.[13]

Figure 12 shows the radial profile of particle transport considering and neglecting the correction of the plasma parameters by the temperature fluctuations. As one can see in this figure, this correction introduces significant alterations on the transport profile.

Edge profiles of the measured plasma parameters, influence of temperature corrections, particle and energy transport, relations of electrostatic and magnetic fluctuations, and other detailed results are published elsewhere.[6,16]

ACKNOWLEDGMENTS

This work was partially supported by the Brazilian governmental agencies FAPESP and CNPq.

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